



# The Universal Solvent: Dissolving and Solving for the Conservation of Water

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## ABSTRACT

Water is frequently described as the universal solvent due to its exceptional capacity to dissolve, suspend, and extract a wide range of substances. Molecular versatility renders water indispensable for sustaining life and facilitating the movement of chemicals and nutrients through terrestrial, atmospheric, and biological systems. Although water serves as a life-sustaining medium, global conservation efforts necessitate innovative and increasingly sophisticated approaches to ensure the continued availability of freshwater resources. The present study examines the fundamental properties of water, analyzes the socio-cultural factors influencing freshwater demand, and highlights emerging scientific and technological advancements designed to strengthen water conservation. The study offers insight into how water-focused content can serve as a rich foundation for interdisciplinary and transdisciplinary teaching and learning across science, technology, engineering, and mathematics (STEM) fields. Curricular exemplars are provided, including aquaponics, urban agriculture, and rainwater harvesting, which can be implemented across the entire educational spectrum, from early childhood through higher education. The study concludes with recommendations to support sustainable water management and guide the development of robust STEM programmatic offerings.

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## INTRODUCTION

Water occupies a central position in natural systems and human development. Its molecular structure and chemical behavior allow it to interact with, transport, and transform a broad spectrum of substances, reinforcing its long-standing designation as the “universal solvent.” These characteristics shape biochemical reactions, geophysical processes, atmospheric dynamics, and the stability of ecosystems. Water’s capacity to dissolve ions, carry nutrients, regulate temperature, and participate in countless chemical pathways makes it a foundational role in sustaining life and moderating Earth’s environment (Skinner & Benmore, 2016).

Growing concerns regarding freshwater scarcity, climate instability, population growth, and global access elevate the urgency of understanding water not only as a scientific subject but also as a socio-ecological resource. Learners must be equipped with the conceptual and practical tools required to interpret water behavior, evaluate conservation needs, and apply scientific knowledge to real-world contexts. A strong grounding in water science strengthens STEM and STEAM (science, technology, engineering, art, and mathematics) education by supporting interdisciplinary inquiry, systems thinking, and environmental literacy, which are essential competencies for addressing global sustainability challenges.

### Properties of Water

Water exhibits a constellation of physical and chemical properties that make it indispensable to biological and ecological systems. Its polarity, hydrogen bonding capacity, and phase-change behaviors influence climate regulation, nutrient circulation, and essential biochemical processes. Understanding these properties provides students with conceptual foundations for analyzing hydrologic cycles, water quality, engineered systems, and conservation practices.

A concise synthesis of water’s defining characteristics can support clearer connections between scientific concepts and instructional applications. Organizing these properties in a comparative format helps readers understand how molecular behavior influences ecological functions and how these concepts can be applied to create meaningful STEM and STEAM learning experiences. **Table 1** summarizes key physical and chemical properties of water and identifies their relevance to both environmental systems and educational practice.

### Composition and Chemical Properties

Although the chemical formula  $\text{H}_2\text{O}$  is introduced early in schooling, the behavior of water reflects a significant level of molecular complexity. Each molecule contains two hydrogen atoms bonded to one oxygen atom through polar covalent bonds. The bent geometry of the molecule and the uneven distribution of electrons produce a dipole that facilitates hydrogen bonding among adjacent molecules (Skinner & Benmore, 2016).

Hydrogen bonding enables water to dissolve many ionic and polar substances, mediate biological reactions, transport nutrients, and influence geochemical transformations. Water also acts as both an acid and a base under different conditions, dissociates ionic compounds, and participates in oxidation and reduction reactions, allowing it to support a wide range of natural and engineered processes (LibreTexts, 2023). These chemical properties explain water’s exceptional solvent capabilities and highlight its central role in environmental chemistry, hydrology, and ecological processes.

### *Melting, Freezing, and Sublimation Points*

Water’s phase changes stem from the interactions among its molecules. Under standard atmospheric pressure, pure water freezes at 0 degrees Celsius and boils at 100 degrees Celsius. These

values shift under changing pressures or solute concentrations. A unique phase condition, known as the triple point, occurs at 0.01 degrees Celsius and 0.00604 atmospheres, where solid, liquid, and vapor phases coexist in equilibrium (Guildner et al., 1976).

**Table 1**  
*Key Properties of Water and Their Educational Significance*

Property	Scientific Description	Ecological Significance	Instructional Application (STEM/STEAM)
Polarity & Hydrogen Bonding	Water molecules are polar and form hydrogen bonds due to unequal charge distribution.	Enables dissolving power, cellular structure stability, and biochemical reactions.	Demonstrations of solubility, molecular modeling, and simulations of intermolecular forces.
High Specific Heat Capacity	Water absorbs large amounts of heat with minimal temperature change.	Moderates climate, stabilizes ecosystems, and maintains organismal homeostasis.	Labs analyzing temperature change, climate modeling activities, and heat-energy experiments.
Cohesion & Adhesion	Strong intermolecular attraction leads to surface tension and capillary movement.	Supports plant transpiration and aquatic habitat formation.	Experiments with capillary tubes, plant physiology investigations, and surface-tension demonstrations.
Density Anomaly (Ice Floats)	Solid water has lower density than liquid water.	Insulates aquatic ecosystems during freezing conditions.	Investigations into freezing/melting, density comparisons, and climate-adaptation case studies.
Phase Changes & Triple Point	Water transitions among solid, liquid, and gas, and exhibits a triple point where all three coexist.	Drives hydrologic and climate processes.	Phase-change experiments, modeling sublimation, and analyzing atmospheric data.

When pressure falls below the triple point threshold, ice transitions directly into vapor through sublimation. This phenomenon is observed in cold, dry climates where snow gradually disappears without melting. Sublimation also supports industrial applications such as freeze-drying processes used for food and pharmaceutical preservation. Understanding these phase relationships strengthens students' ability to analyze atmospheric behavior, model hydrologic processes, and examine climate-related variations.

### Physical Properties

Water's physical properties reinforce its ecological and biological significance. Pure water is colorless, odorless, and tasteless; yet, its molecular organization produces strong intermolecular attractions. High surface tension and cohesion enable capillary action, stabilize cellular structures, and support biological and botanical functions (Fathi-Azarbayjani & Jouyban, 2015).

Water has a high specific heat capacity that allows it to absorb large amounts of energy with minimal temperature change. This moderating effect stabilizes aquatic environments, regulates global climate patterns, and supports internal temperature regulation across species (LibreTexts, 2023). Water's high heat of vaporization enables evaporative cooling through perspiration and transpiration. These thermal properties help students understand how ecosystems respond to temperature variation, how engineered systems regulate heat, and how conservation strategies consider thermal dynamics in natural settings.

### **Involvement in Natural Processes**

Water functions as a unifying medium across atmospheric, terrestrial, oceanic, and biological systems. Its continuous movement across these domains reflects the Law of Conservation of Mass. Water is not created or destroyed but is transformed and redistributed through natural cycles that sustain biochemical reactions, nutrient circulation, weather regulation, and overall ecosystem productivity.

Two major biogeochemical cycles, the Carbon Cycle and the Water Cycle, illustrate water's integrative role in environmental functioning.

#### ***Carbon Cycle***

Carbon circulates through ecosystems via photosynthesis, respiration, decomposition, and sedimentation. Water facilitates many of these transformations. During photosynthesis, plants and algae use water and carbon dioxide to synthesize carbohydrates, releasing oxygen as a byproduct. Respiration and decomposition processes return carbon dioxide to the atmosphere and hydrosphere, while sedimentation stores carbon in soils, oceans, and geological formations.

Human activity has altered the carbon balance by rapidly increasing atmospheric carbon dioxide through fossil fuel combustion. Oceans absorb substantial quantities of this excess carbon and serve as major carbon sinks (Skinner & Benmore, 2016). Water's capacity to dissolve, transport, and transform carbon compounds highlights its essential role in regulating global climate systems.

#### ***Water Cycle***

The Water Cycle describes the continual movement of water across Earth's systems. Evaporation introduces water vapor into the atmosphere. Condensation forms clouds, and precipitation returns water to the surface. Runoff, infiltration, groundwater recharge, and surface flow redistribute water across landscapes before evaporation begins again (Ramachandran et al., 2021).

These cyclical movements shape weather patterns, maintain freshwater supplies, support agriculture, and sustain ecological systems. Although water is renewable, human practices such as deforestation, groundwater depletion, pollution, and emissions-driven climate change threaten the reliability of the water cycle. Understanding this cycle helps learners develop essential environmental literacy and prepares them to evaluate hydrologic systems, conservation needs, and sustainable water management practices.

### **Socio-Cultural Importance**

Water holds significant socio-cultural, economic, and political importance for societies throughout history and around the world. Its centrality to human survival makes access to freshwater a foundational requirement for the development of cultures, communities, and governing institutions. Although Earth is predominantly covered by water, only a small fraction is potable, leaving many regions vulnerable to water scarcity. Drinking water is indispensable; yet, the broader uses of water, including agriculture, sanitation, industry, and food preparation, render it essential for every aspect of human life.

Throughout history, the rise and decline of civilizations have often hinged on the availability, distribution, and management of freshwater resources. Conflicts over water access have been documented from antiquity to the present day. For example, during the Syrian Civil War, control of a major dam became a strategic mechanism through which rebel groups sought leverage over government forces (Unfried et al., 2022). Water stress is now recognized as a global concern, with approximately 25% of large cities experiencing moderate to severe water scarcity. Projections indicate that global water

demand will increase by 55% by 2030, heightening the risk of conflict, migration, and ecological disruption (Salehi, 2021). Although the geopolitical contexts of water disputes have evolved, the underlying challenge remains the same: securing reliable access to freshwater.

### Global Patterns in Water Availability and Scarcity

Freshwater availability varies widely across regions due to climatic conditions, population pressures, governance systems, and technological capacity. A comparative analysis of global data reveals several patterns that shape both environmental sustainability and the educational implications of water science. UN Water (2021) identifies substantial geographic variability in water stress, with some nations experiencing chronic scarcity and others facing challenges related to water quality, distribution, or infrastructure.

Comparing these regional differences offers a clearer understanding of how environmental, infrastructural, and political factors intersect to shape global water conditions. A structured synthesis also highlights the distinct challenges faced by communities and ecosystems, while illustrating the range of instructional opportunities that emerge from these variations. **Table 2** summarizes the major regional patterns in water availability and scarcity, and outlines related educational implications that support deeper engagement with water science across various learning environments.

**Table 2**

*Global Water Challenges and Educational Implications across Regions*

Region	Primary Water Challenges	Underlying Causes	Educational Implications
North America	Local scarcity, aging infrastructure, contamination events	Overuse, industrial runoff, climate variability	Lessons on watershed management, water-quality testing, and policy analysis.
South America	Pollution, uneven distribution	Urbanization, mining impacts	Inquiry on ecosystem health, water-rights debates, and conservation strategies.
Africa	Extreme scarcity, drought, access	Climate change, inadequate infrastructure	Projects on groundwater systems, desalination design, and community-based solutions.
Europe	Pollutant load, extreme weather	Agricultural runoff, climate patterns	Investigations on sustainable agriculture, hydrology modeling, and water recycling.
Asia	Over-extraction, pollution, high demand	Industrialization, population growth	Units on aquaculture impacts, filtration engineering, and conservation technology.
Australia & Oceania	Chronic drought, salinity	Climate instability, limited freshwater	Integrated climate-water studies, drought-resilience projects, and desalination studies.

### Regions Facing Chronic Water Scarcity

High and extreme levels of water stress are concentrated across western, central, and southern Asia, including the Middle East and North Africa (MENA). These regions receive minimal annual precipitation, rely heavily on groundwater extraction, and experience rapid population growth (Ragheb, 2017; UN Water, 2021). Desalination has emerged as a dominant technological response; as of 2020, the MENA region accounted for approximately 30% of the world's desalination plants and nearly half of global desalination capacity (Eke et al., 2020; Elsaid et al., 2020). Although membrane-based

technologies, particularly reverse osmosis, expand freshwater supplies, they remain energy-intensive, costly, and environmentally burdensome. Educators in these regions increasingly frame water literacy through the lens of engineering constraints, sustainability ethics, and the limits of technological intervention in addressing structural scarcity.

### ***Regions with High Water Quality and Challenged Access***

Several nations in North America, South America, and Europe possess abundant freshwater resources, yet internal disparities persist. Despite strong regulatory systems, the United States continues to experience accessibility issues to safe drinking water and areas of chronic underinvestment (Tong et al., 2020; UN Water, 2021). Mexico and parts of South America similarly report uneven access between urban and rural regions. Although Canada maintains some of the highest-quality freshwater reserves globally, disparities remain among remote communities (UN Water, 2021). These patterns accentuate the importance of incorporating topics related to environmental justice, infrastructure, and the social determinants of water access into STEM and STEAM curricula.

### ***Regions with Advanced Conservation and Technological Interventions***

Highly industrialized regions employ large-scale conservation approaches and technological solutions. In the European Union, circular economy models prioritize wastewater recovery, resource reuse, and waste minimization to reduce freshwater extraction (Koseoglu-Imer et al., 2023). Hydropower remains a significant renewable energy source in countries such as Norway, Poland, Peru, and Brazil, though its long-term viability depends on stable precipitation and river flow (Borowski, 2022; Marengo et al., 2014). These technological interventions demonstrate the convergence of engineering, policy, and sustainability, an essential interdisciplinary connection for water-focused STEM and STEAM education.

### ***Regions Where Climate Change Is Altering Hydrological Cycles***

Climate change is reshaping water availability worldwide. Increased evapotranspiration in the Amazon Basin, prolonged droughts in Africa, reduced snowpack in the Andes, and intensified heatwaves across Europe all indicate shifting hydrological baselines (Leal Filho et al., 2022; Marengo et al., 2014). These disruptions threaten agricultural productivity, biodiversity, and long-term water security. For education, these phenomena provide authentic contexts for hydrological modeling, climate data analysis, and understanding the environmental variables that shape regional water systems.

### ***Regions Experiencing Sociopolitical Conflict over Water***

Water scarcity contributes to sociopolitical instability in several regions. Disputes over shared river systems, such as the Nile Basin involving Ethiopia, Sudan, and Egypt, illustrate how water access influences geopolitical relations (Unfried et al., 2022). Internal conflicts have also emerged where scarcity intersects with agricultural competition or infrastructure failure, such as farmer–herder conflicts in Nigeria or pipeline breakdowns in Senegal (Unfried et al., 2022; Leal Filho et al., 2022). These examples highlight the importance of integrating policy analysis, resource governance, and social science perspectives into water-focused STEM education.

### ***Historical Context: Water as the Foundation of Civilization***

Across time, civilizations have developed in close proximity to reliable water sources. Early societies, including those in Ancient Mesopotamia, Egypt, China, India, Greece, and Rome, constructed complex hydraulic systems such as canals, aqueducts, and irrigation networks that enabled agriculture, transportation, and urbanization (Maisels, 2005; Hansen, 1983; Hosseiny et al., 2021; Ramesh, 2018).



In the Andean region, the Inca engineered sophisticated terraced landscapes and water-distribution channels that integrated geology, agriculture, and spiritual beliefs (Bray, 2013; Cartwright, 2014; Mazadiego et al., 2009). These historical patterns reflect a universal reliance on water for social, economic, and political development (Damen, 2019; Drake, et al., 2011). They also highlight the longstanding human endeavor to understand, manage, and engineer water systems—an insight that enriches contemporary STEM and STEAM curricular approaches focused on sustainability, design thinking, and systems analysis.

## **EDUCATIONAL IMPLICATIONS AND WATER PATTERNS**

A global review of water systems illustrates why water literacy must be a central component of STEM and STEAM education from early childhood through higher education. Understanding water scarcity, hydrological variability, and conservation technologies helps students develop systems thinking, ethical reasoning, and evidence-based problem-solving skills (UN Water, 2021; Koseoglu-Imer et al., 2023). The scientific and sociopolitical dimensions of water, ranging from desalination engineering to transboundary conflict, provide compelling interdisciplinary contexts for inquiry-based instruction, design challenges, and community-engaged research. Integrating these global patterns into education prepares learners to address contemporary sustainability challenges and contribute to the responsible stewardship of Earth's most critical solvent.

### **The Nature of Conservancy**

Water conservancy encompasses the protection, management, and sustainable use of freshwater resources across ecological, social, and economic domains. At its core, conservancy recognizes water as a finite and shared resource whose availability is shaped by climatic variability, population growth, technological capacity, and governance structures. Effective conservancy efforts require an understanding that freshwater systems are interconnected and influenced by both natural processes and human activity. Conservancy therefore emphasizes stewardship and the long-term resilience of water systems that support both human and nonhuman life.

### **Current Conservation Efforts**

Across the globe, communities, governments, and organizations are implementing a range of strategies to preserve freshwater resources. These efforts include improved wastewater treatment, expanded monitoring of surface and groundwater quality, policy frameworks that regulate industrial discharge, and initiatives to reduce agricultural water consumption. Many countries have developed national adaptation plans to address water scarcity, although implementation varies widely (Encyclopedia Britannica, 2019; Fang & Jawitz, 2019). Educational institutions also play a meaningful role by integrating water science into STEM and STEAM curricula, thereby preparing learners to engage with contemporary conservation challenges through inquiry, analysis, and problem-solving.

### **Innovative Conservation Efforts**

Advances in science and technology have generated new approaches to water conservation that extend beyond traditional management practices. Emerging methods include aquaponics and hydroponics systems that reduce agricultural water use, decentralized rainwater harvesting technologies, atmospheric water generation, and membrane-based purification systems. At the municipal and industrial levels, innovations such as circular economy wastewater reuse, bioswale integration, smart metering infrastructure, and precision irrigation systems enhance efficiency and reduce losses. These innovations highlight the potential for interdisciplinary collaboration to strengthen water security while also enriching learning experiences across STEM fields.

## **CONNECTING CONSERVATION AND STEM**

Collectively, the global patterns outlined above demonstrate that water availability is shaped not only by natural hydrological processes but also by governance systems, technological capacity, and socio-economic conditions (Fang & Jawitz, 2019). These patterns reveal why conservation outcomes vary widely across regions and why even technologically advanced nations experience vulnerability when infrastructure, policy, or community engagement fall short.

In addition, they demonstrate why STEM and STEAM education must prepare learners to evaluate conservation challenges through scientific, engineering, and socio-political lenses. By situating global patterns alongside local contexts, educators and policymakers can better understand why conservation efforts break down and what future strategies will be required to safeguard freshwater resources. Understanding these dynamics provides essential context for examining the conditions under which conservation succeeds or fails and for identifying the strategies needed to strengthen water security on a global scale (UN Water, 2021; Koseoglu-Imer et al., 2023).

### **When Conservation Fails**

Despite global progress, conservation efforts can fail when governance systems, infrastructure, or community engagement are insufficient to meet environmental and societal demands. Failures may occur when resource extraction exceeds natural replenishment rates, when policy implementation lags behind scientific understanding, or when climate-related events intensify faster than anticipated. In many regions, inadequate funding, weak regulatory enforcement, and geopolitical conflict further hinder conservation. Such failures often result in diminished water quality, ecosystem degradation, public health crises, and social instability, underscoring the urgency of sustainable and adaptive water management.

### **Future Conservation Considerations**

Looking forward, water conservation will require integrative, collaborative, and adaptive strategies informed by science, technology, and education (Hartig et al., 2020; Kempe, 2006). Key priorities include expanding access to safe drinking water, strengthening climate-resilient infrastructure, scaling up renewable-energy-supported desalination technologies, and enhancing watershed protection. Future efforts must also center on community participation, Indigenous knowledge systems, and interdisciplinary research to ensure that conservation practices address both local needs and global sustainability goals. By cultivating water literacy and fostering innovation within STEM and STEAM education, future generations will be better prepared to protect the world's most critical natural resource.

## **DISCUSSION**

Water is indispensable to the continuity of life, ecological resilience, and global social stability. Its unique chemical and physical properties make it foundational to natural processes, economic development, and public health. Yet its availability is increasingly challenged by population growth, climate change, and access. This article highlights the scientific dimensions of water, the socio-cultural and geopolitical complexities that influence freshwater distribution, and the conservation strategies employed across continents.

Education plays a pivotal role in addressing these challenges. From early childhood through higher education, learners benefit from opportunities to explore water in a scientific, ecological, cultural, and ethical context. Water studies foster inquiry, systems thinking, and environmental literacy, competencies essential for navigating the complexities of global sustainability. Integration of water science in STEM and STEAM programs cultivates an informed citizenry capable of understanding both

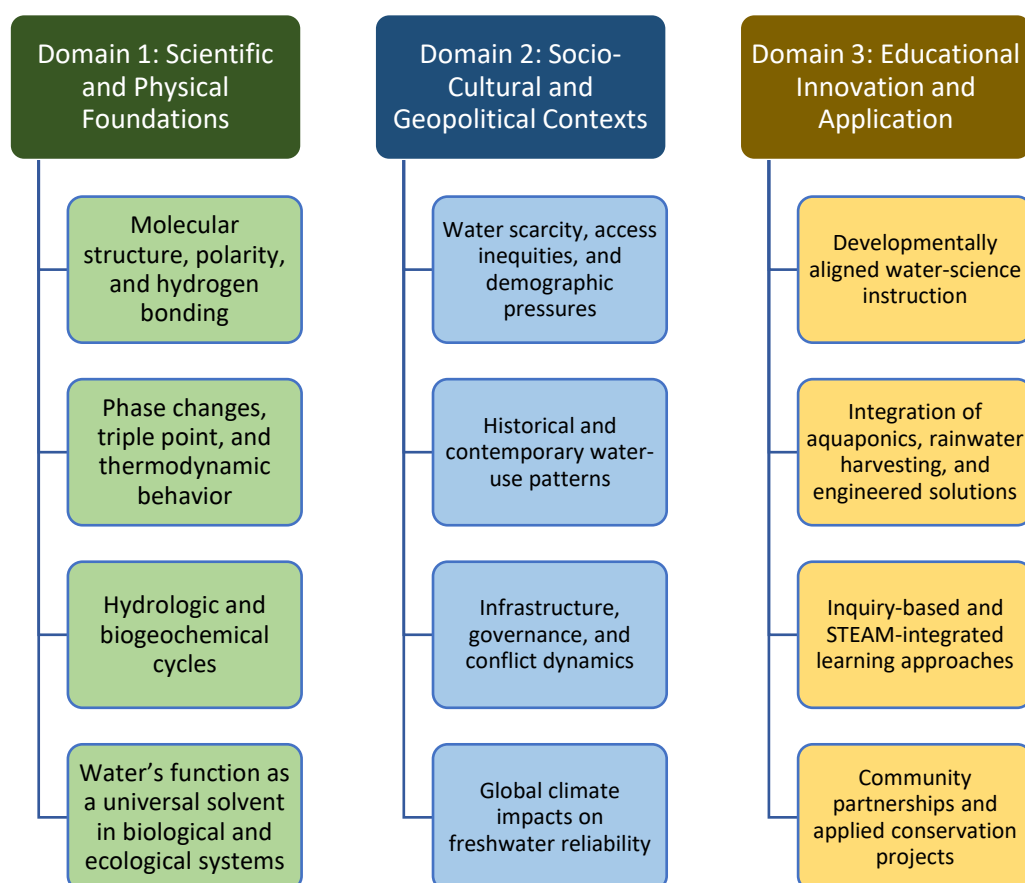


the urgency of water conservation and the innovative strategies required to safeguard freshwater systems.

Environmental education initiatives significantly contribute to conservation outcomes by enhancing learners' ecological knowledge, fostering stewardship behaviors, and cultivating a sense of environmental responsibility. Engagement in community-based and citizen science projects strengthens students' ability to analyze local ecological challenges and contribute meaningfully to conservation efforts (Ardoin et al., 2020). These experiences support the development of applied scientific reasoning and instill a sense of agency in addressing sustainability issues.

Advances in rainwater harvesting also demonstrate the importance of preparing learners for emerging water technologies. Rainwater harvesting (RWH) systems offer sustainable alternatives for communities facing climate variability, drought, and water supply stress. Students who explore such systems gain insight into decentralized water infrastructure, climate-adaptive design, and long-term resilience planning (Raimondi et al., 2023). These insights emphasize the importance of educational pathways that equip learners to engage with complex, technology-driven conservation strategies.

**Figure 1**  
*Water Literacy*



A unifying framework can help consolidate the scientific, socio-cultural, and educational dimensions discussed above and clarify how they collectively support comprehensive water literacy. Presenting these dimensions in visual form highlights the relational structure that underpins effective water-science education and prepares readers for the instructional recommendations that follow. **Figure 1** illustrates the three interconnected domains that guide the development of water literacy across educational contexts.

## **RECOMMENDATIONS**

### **Early Childhood Education**

Early childhood settings offer valuable opportunities for learners to develop a foundational understanding of water through sensory exploration, guided observation, and emergent inquiry. Experiences with water tables, rainfall, puddles, and plant watering strengthen early scientific reasoning and nurture curiosity about natural systems (Million et al., 2016). Young learners benefit from simple, play-based demonstrations that reveal how water travels across various surfaces, supporting an early awareness of infiltration, runoff, and the directional movement of water in their immediate environment (Texas A&M AgriLife Extension Service, 2014). These experiences help children visualize basic watershed concepts and recognize how topography influences the flow of water.

Hands-on engagements also introduce young learners to early conservation principles. Activities that demonstrate how water can be absorbed, wasted, or shared across a landscape foster an appreciation for water as a finite resource that requires shared responsibility (Texas A&M AgriLife Extension Service, 2014; Steglich et al., 2020). Such explorations foster emerging environmental empathy and lay the groundwork for understanding that the care of local water systems relies on collective human action. Instruction that frames water as both essential and interconnected across living systems encourages children to develop early dispositions toward stewardship, laying the groundwork for later environmental literacy.

### **Elementary Education**

Elementary students deepen their comprehension of water through structured investigations that link scientific principles to local environmental contexts. The study of the water cycle, states of matter, and basic conservation practices can be enriched through schoolyard observations, rainwater collection demonstrations, and inquiries into community water sources. Activities that illustrate how different land covers influence rainfall infiltration, runoff, and soil stability help students understand the relationship between land management and water behavior (Texas A&M AgriLife Extension Service, 2014). These demonstrations also highlight the ecological importance of vegetation in mitigating runoff and preventing erosion.

Students benefit from experiments that examine how soil type, ground cover, and surface conditions impact erosion rates and water absorption. Such activities strengthen competencies in data collection, measurement, and early quantitative reasoning while enabling learners to interpret environmental patterns through evidence-based explanations (Texas A&M AgriLife Extension Service, 2014; Steglich et al., 2020). Introductory watershed models allow students to visualize how water flows from higher to lower elevations and how human decisions influence water quality and availability.

Early applications of rainwater-harvesting concepts can further enrich students' understanding of sustainable water practices. Simple catchment models, gutter simulations, or hands-on demonstrations of slow-release irrigation provide tangible examples of how water can be captured, stored, and reused. These experiences bridge scientific understanding with practical problem-solving, introducing learners to conservation strategies that support agricultural productivity, ecological stability, and responsible community water use. Integrating these activities within interdisciplinary lessons helps students connect water science to geography, civic responsibility, and environmental decision-making (Million et al., 2016).

### **Middle School Education**

Middle school learners benefit from opportunities to examine water systems through hands-on,

inquiry-driven investigations. Projects focused on water quality, pollution, and ecosystem interactions promote the development of scientific reasoning and analytical skills. Engagement with engineering design challenges, such as modeling aquifers, constructing filtration systems, or analyzing local watershed data, strengthens students' ability to evaluate environmental problems and consider viable solutions. STEAM-integrated units further encourage critical and creative approaches to understanding human–environment relationships.

Aquaponics provides middle school students with opportunities to observe ecological interactions, nutrient cycles, and organism relationships within a living system. These experiences promote experiential learning by allowing students to link scientific concepts to observable processes (Bice et al., 2020; Mortaza et al., 2021). Engagement with classroom growing systems broadens students' ecological understanding and fosters interdisciplinary thinking.

Teachers implementing aquaponics benefit from support related to system operation, curricular alignment, and maintenance procedures. Professional learning enhances educators' capacity to guide inquiry-based instruction and integrate aquaponics into standards-based science curricula (Bice et al., 2020; Steglich et al., 2020).

### **High School Education**

High school learners are developmentally prepared to engage with advanced scientific investigations that explore hydrology, environmental chemistry, and global water inequities. Instruction at this level can incorporate collaborative research, system-based agricultural models, digital data collection tools, and critical analysis of contemporary water policy debates (Mortaza et al., 2021). Experiences that integrate scientific content with real-world case studies deepen analytical competencies and strengthen students' ability to evaluate complex socio-environmental issues.

Participation in project-based aquaponics curricula improves students' understanding of ecosystems, ecological relationships, and environmental interdependence. Collaborative experimentation and system management promote deeper conceptual reasoning and increase student motivation (Million et al., 2016; Thompson et al., 2023).

Aquaponics also supports STEM integration by requiring students to apply scientific inquiry, engineering design principles, and collaborative problem solving. Exposure to aquaponics systems heightens students' awareness of sustainable agriculture, responsible water use, and real-world environmental challenges (Baykir et al., 2023).

Rainwater harvesting can deepen high school students' understanding of sustainable water management. Engagement with RWH technologies helps learners evaluate water scarcity, agricultural water needs, and the role of conservation in global food systems (Steglich et al., 2020; Velasco-Muñoz et al., 2019).

### **Higher Education**

Universities serve as critical environments for interdisciplinary exploration of water-related challenges that span science, technology, society, and policy. Coursework and research opportunities can emphasize sustainable agriculture, water engineering, environmental chemistry, and conservation technologies. Partnerships with agencies, community organizations, and international institutions provide authentic contexts for experiential learning and applied problem solving in water sustainability fields.

Students at the university level benefit from direct engagement with rainwater harvesting research, which introduces emerging technologies in decentralized water treatment, sustainable

infrastructure design, and climate-resilient systems. Exposure to these topics strengthens interdisciplinary research capacities and prepares learners for careers in water sustainability fields (Mortaza et al., 2021; Raimondi et al., 2023).

A coherent progression of learning experiences ensures that water science is introduced, reinforced, and extended in developmentally appropriate ways across educational levels. Aligning core concepts with instructional practices strengthens curricular design and supports the cultivation of environmental literacy from early childhood through higher education. **Table 3** outlines a recommended learning progression that integrates scientific understanding, hands-on engagement, and research-supported instructional strategies across the full educational continuum.

**Table 3**

*Water-Science Learning Progression from Early Childhood to Higher Education*

<b>Educational Level</b>	<b>Core Water Concepts</b>	<b>Recommended Activities</b>
Early Childhood	Water as a natural, shared resource; sensory properties	Water tables, guided observation, structured play
Elementary	Water cycle, states of matter, local sources	Rainwater collection, campus gardens, simple filtration
Middle School	Water quality, ecosystems, human impacts	Water-testing kits, aquifer models, school wetlands
High School	Hydrology, global inequities, engineered solutions	Aquaponics systems, GIS mapping, policy debates
Higher Education	Sustainable engineering, conservation technologies	Research labs, RWH design, field partnerships

### **Teacher Preparation and Professional Development**

Preparation programs for educators can strengthen pedagogical capacity by emphasizing inquiry-based science instruction, culturally responsive practices, and alignment with national and international water-literacy standards. Collaborative efforts among education, engineering, and environmental science programs support the development of interdisciplinary teaching strategies that enable educators to integrate water science effectively across grade levels and learning environments.

Teacher preparation programs can enhance instructional quality by helping educators understand aquaponics as a STEM integration tool. Training that emphasizes scientific inquiry, engineering design processes, and hands-on experimentation strengthens teachers' capacity to guide students through complex ecological investigations (Baykir et al., 2023).

Professional development should also address common implementation challenges such as maintaining aquaponics systems, managing interdisciplinary content, and integrating activities with existing curricular structures. Support in these areas increases teacher confidence and improves the effectiveness of aquaponics-based instruction (Bice et al., 2020).

### **Educational Policy and Institutional Support**

Educational institutions can advance sustainability goals through policies that promote water conservation, environmental stewardship, and community-engaged learning. Strategic investments in green infrastructure—such as bioswales, rain gardens, and efficient irrigation systems—allow schools and universities to model responsible resource management while enhancing the campus environment as a living laboratory for students.

Institutional adoption of rainwater harvesting systems can strengthen school sustainability efforts by reducing strain on local water resources and providing authentic learning environments for students. Such systems help campuses model water-resilient practices while advancing conservation goals (Velasco-Muñoz et al., 2019).

Rainwater-harvesting infrastructure also contributes to broader climate-adaptation strategies by offering decentralized water sources that support communities during drought or extreme weather events. Schoolwide integration of such technologies strengthens environmental resilience and aligns educational institutions with global sustainability priorities (Raimondi et al., 2023; Steglich et al., 2020).

## CONCLUSION

Water's scientific, ecological, and socio-cultural importance affirms its status as one of the most critical resources for sustaining life and supporting global development. The analysis presented in this article demonstrates how water's molecular properties underpin natural processes, shape environmental conditions, and influence the stability of human systems. The global review of freshwater challenges reveals that water availability is governed not only by hydrological factors but also by technological capacity, infrastructure quality, governance, and long-term environmental change. These intersecting dimensions position water as a central subject for interdisciplinary inquiry and a unifying theme for STEM and STEAM education.

The integration of water science into educational settings equips learners with the analytical tools necessary to examine real-world environmental issues, evaluate conservation strategies, and engage in evidence-based problem-solving. Classroom experiences that incorporate aquaponics, rainwater harvesting, and other applied technologies help students connect scientific concepts to tangible environmental and community needs. Such approaches enhance environmental literacy, foster systems thinking, and support the development of informed and responsible decision-makers.

Ongoing global challenges, including climate variability, water scarcity, and infrastructure necessities, highlight the need for educational pathways that equip learners to comprehend and address emerging water-related issues. Conservation efforts will depend on individuals who can interpret scientific data, evaluate engineered solutions, understand socio-political contexts, and collaborate across disciplines. Educational institutions, therefore, play a crucial role in cultivating the next generation of scientists, engineers, policymakers, and community leaders who will be responsible for stewarding the Earth's freshwater systems.

A sustained commitment to water literacy enriches both scientific understanding and civic engagement. Learners who explore water through scientific, historical, cultural, and technological perspectives gain a deeper appreciation for the complexity of freshwater systems and the collective responsibility required to protect them. Strengthening water-focused education from early childhood through higher education ensures that future generations are prepared to participate in the stewardship, innovation, and collaborative problem-solving that will shape global water sustainability.

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